Appendix B
Power Transformer Studies and Calculations

B-1. Recommended Studies

a. The following studies should be performed during the preliminary design phase for generator step-up power transformers:

(1) Transformer *kVA* Rating Study.

(2) Transformer Cooling Study.

(3) Basic Impulse Insulation Level (BIL) / Surge Arrester Coordination Study.

(4) Transformer Bushings Rating Study.

(5) Transformer Efficiency Study.

(6) Transformer Loss Evaluation Study.

(7) System Fault Study for Transformer Impedance Determination.

b. This appendix outlines samples of these studies and calculations as listed above. Sample studies for items (a) and (b) are not included due to their lesser degree of complexity and site-specific nature (a discussion concerning transformer ratings and cooling considerations is included in Chapter 4). A system fault study should be performed prior to determining transformer impedances. A sample system fault study is not included in this appendix due to its expanded scope and site-specific nature.

B-2. Data Used for Sample Studies

a. The sample studies shall be based upon the following assumed data:

(1) Transmission line data:

- 230 $kV_{L\text{-}L}$
- 750 *kV* BIL rating

(2) Generator data:

- 69,000 *kVA*
- 110 *kV* winding BIL

(3) Transformer data:

- 46,000 *kVA*
- 13.2 *kV*/115 *kV*
- two-winding
- 1ϕ
- FOA type cooling

B-3. Sample Study B1, BIL / Surge Arrester Coordination

a. Objective.

The objective of this study is to determine the following:

(1) Transformer high-voltage basic impulse insulation levels (BIL's).

(2) Transformer impulse curves.

(3) Surge arrester type and sizing.

(4) Surge arrester impulse curves.

(5) Transformer high-voltage BIL / surge arrester coordination.

b. References.

The following references were used in the performance of this study. Complete citations can be found in Appendix A of this document, "References."

(1) ANSI C62.1-1984.

(2) ANSI C62.2-1987.

(3) ANSI C62.11-1987.

(4) ANSI/IEEE C57.12.00-1987.

(5) ANSI/IEEE C57.12.14-1982.

(6) ANSI/IEEE C57.12.90-1987.

(7) ANSI/IEEE C57.98-1986.

c. Procedure. The proposed transformer replacement will be two winding, single-phase, 60-Hz, FOA cooled units, 65 °C rise, connected delta/wye, with the following ratings:

Transformer bank: Three-1ϕ, 46,000 *kVA*, 13.2 *kV*/230 *kV*.

These transformers are considered to be a "replacement-in-kind."

(1) *Transformer high-voltage basic impulse insulation levels (BIL's).*

(a) Line BIL characteristics. The Power Marketing Authority's (PMA's) transmission line, transformer high-voltage insulation, high-voltage bushing BIL characteristics, and surge arrester duty-cycle ratings are as follows:

230-*kV* System:

- Transmission line: approximately 750 *kV* BIL
- Transformer high-voltage insulation: typically 650 *kV* BIL
- High-voltage bushings: typically 750 *kV* BIL
- Surge arrester rating: typically 180 *kV* duty-cycle rating

(b) This study will analyze transformer high-voltage BIL levels of 650 *kV*, 750 *kV*, and 825 *kV*, for the 230-*kV* transmission line, and determine the correct level of protection.

(2) *Transformer impulse curves.*

(a) Front-Of-Wave (FOW) withstand voltage.

As indicated by ANSI C62.2, the FOW strength range should be between 1.3 and 1.5 times the BIL rating, with time-to-chop occurring at 0.5 µs. For the purposes of this coordination study, an FOW strength of 1.4 times BIL shall be used.

Table B-1
FOW Withstand Voltage

Line Voltage, kV	BIL Rating, kV	FOW Strength, kV
230	650	910
230	750	1050
230	825	1155

(b) Chopped-wave (CWW) withstand voltage.

Chopped-wave withstand voltage levels for different transformer high-voltage BIL ratings are listed in Table 5 of ANSI/IEEE C57.12.00. These levels correspond to 1.1 × BIL, and the time-to-chop occurs at 3.0 µs.

Table B-2
CWW Withstand Voltage

Line Voltage, kV	BIL Rating, kV	CWW Strength, kV
230	650	715
230	750	825
230	825	905

(c) Full-wave (BIL) withstand voltage.

The full-wave withstand voltage is equivalent to the high-voltage BIL rating of the transformer. This withstand voltage occurs as a straight line from 8 to 50 µsec.

(d) Switching impulse level (BSL) withstand voltage.

Switching impulse withstand voltage levels for different transformer high-voltage BIL ratings are listed in Table 5 of ANSI/IEEE C57.12.00. These levels correspond to 0.83 × BIL, and extend from 50 to 2,000 µsec.

Table B-3
BSL Withstand Voltage

Line Voltage, kV	BIL Rating, kV	BSL Strength, kV
230	650	540
230	750	620
230	825	685

(e) Applied voltage test level.

Applied voltage test levels for different transformer high-voltage BIL ratings are listed in Table 5 of ANSI/IEEE C57.12.00.

Table B-4
APP Voltage

Line Voltage, kV	BIL Rating, kV	APP Strength, kV
230	650	275
230	750	325
230	825	360

(f) Transformer impulse curve generation. The transformer impulse curve is generated as indicated in Figure 3 of ANSI C62.2. As discussed in Figure 3:

> It is not possible to interpolate exactly between points on the curve. Good experience has been obtained with the assumptions implicit in the preceding rules: (a) The full BIL strength will apply for front times between 8 and 50 µs. (b) Minimum switching surge withstand occurs between 50 and 2,000 µs. Refer to the attached plot of the transformer impulse curves located at the end of this study.

(3) *Surge arrester type and sizing.*

(a) General. The objective for surge protection of a power system is to achieve at a minimum cost an acceptably low level of service interruptions and an acceptably low level of transformer failures due to surge-related events.

(b) Arrester type. Surge arresters utilizing metal-oxide (such as zinc-oxide) valve (MOV) elements will be used due to the extreme improvement in nonlinearity as compared to arresters with silicon-carbide valve elements. This nonlinear characteristic of the voltage-current curve provides better transformer protection and improves the arrester's thermal stability.

(c) Arrester class. Station class arresters shall be utilized, based on system line voltage of 230 *kV*.

(d) Arrester sizing. It is desirable to select the minimum-sized arrester that will adequately protect the transformer insulation from damaging overvoltages, while not self-destructing under any reasonably possible series of events at the location in the system. Since the metal-oxide valve in MOV arresters carries all or a substantial portion of total arrester continuous operating voltage, the most important criterion for selection of the minimum arrester size is the continuous operating voltage. Selection of a size for an arrester to be installed on grounded neutral systems is based upon:

- The maximum continuous operating voltage (MCOV), line-to-neutral, at the arrester location computed as the maximum system voltages divided by root-three.

- The assumption that the system is effectively grounded where a fault is expected to initiate circuit breaker operation within a few cycles.

(e) Minimum arrester sizing for system line voltage. Based upon ANSI C57.12.00, the relationship of nominal system voltage to maximum system voltage is as follows:

Nominal System Voltage	Maximum System Voltage
230 *kV*	242 *kV*

(4) The minimum arrester sizing in MCOV for the system line voltage shall, therefore, be as follows:

- Arrester MCOV rating = 242 kV / $\sqrt{3}$ = 139.7 $kV_{1\text{-}n}$

- This calculated arrester rating of 139.7 $kV_{1\text{-}n}$ MCOV for the 230-*kV* line voltage corresponds to a standard arrester voltage rating of 140 $kV_{1\text{-}n}$ MCOV and a duty-cycle voltage of 172 $kV_{1\text{-}n}$, as outlined in Table 1 of ANSI C62.11.

(5) Line voltages at the powerhouse are commonly operated between the nominal and maximum system voltages. Based on this, the surge arrester should be sized somewhat higher than the maximum system line-to-neutral voltage rating of the line to avoid overheating of the arrester during normal operating conditions. The arrester rating chosen shall be one MCOV step higher than the recommended MCOV for grounded neutral circuits. The following arrester MCOV values have been chosen:

- Arrester MCOV rating = 144 *kV*

- Arrester duty-cycle rating = 180 *kV*

B-4. Surge Arrester Impulse Curves

For the purposes of this coordination study, surge arrester voltage withstand levels shall be assumed to correspond to typical manufacturer's data. These voltage withstand levels shall be used for the generation of the arrester curves and the coordination study. Gapped design MOV surge arresters are typically used for distribution class transformers. The gapless design surge arrester shall be addressed in this study, since it represents a typical MOV type arrester suitable for these applications.

a. Maximum 0.5 µs discharge voltage (FOW). The discharge voltage for an impulse current wave which produces a voltage wave cresting in 0.5 µs is correlative to the front-of-wave sparkover point. The discharge currents used for station class arresters are 10 kA for arrester

MCOV from 2.6 through 245 *kV*. As taken from the manufacturer's protective characteristics,

230 *kV* line voltage (144 *kV* arrester MCOV)

Maximum 0.5 µs discharge voltage = 458 *kV*

b. Maximum 8 × 20 µs current discharge voltage (LPL). Discharge voltages resulting when ANSI 8 × 20 µs current impulses are discharged through the arrester are listed in the manufacturer's data from 1.5 kA through 40 kA. For coordination of the 8 × 20 µs current-wave discharge voltage with full-wave transformer withstand voltage, a value of coordination current must be selected. To accurately determine the maximum discharge currents, the PMA was contacted and the following line fault currents were obtained:

Transmission Line (230 *kV*):
3ϕ fault................17010 Amperes
line-ground fault..15910 Amperes

c. Maximum switching surge protective level (SSP). The fast switching surge (45 × 90 µs) discharge voltage defines the arresters' switching surge protective level. As taken from the manufacturer's protective characteristics,

230 *kV* line voltage (144 *kV* arrester MCOV)

Maximum switching surge protective level at classifying 1,000 ampere current level = 339 *kV*.

d. 60-Hz temporary overvoltage capability. Surge arresters may infrequently be required to withstand a 60-Hz voltage in excess of MCOV. The most common cause is a voltage rise on unfaulted phases during a line-to-ground fault. For the arrester being addressed for the purposes of this coordination, the arrester could be energized at 1.37 × MCOV for a period of 1 min.

230-*kV* line voltage (144-*kV* arrester MCOV)

60-Hz temporary overvoltage capability:
144 *kV* × 1.37 = 197.3 *kV*

B-5. Transformer High-Voltage BIL/Surge Arrester Coordination

a. Coordination between MOV arresters and transformer insulation is checked by comparing the following points of transformer withstand and arrester protective levels on the impulse curve plot:

Table B-5
Surge Arrester Coordination

MOV Arrester Protective Level	Transformer Withstand Level
Maximum 0.5 µs discharge voltage - "FOW"	Chopped-wave withstand - "CWW"
Maximum 8 × 20 µs current discharge voltage - "LPL"	Full-wave withstand - "BIL"
Maximum switching surge 45 × 90 µs discharge voltage - "SSP"	Switching surge withstand - "BSL"

b. At each of the above three points on the transformer withstand curve, a protective margin with respect to the surge arrester protective curves is calculated as:

$$\%\ \text{PM} = \left[\frac{(\text{Transformer Withstand})}{(\text{Protective Level})} - 1\right] \times 100$$

c. The protective margin limits for coordination, as specified in ANSI C62.2, are as follows:

(1) % PM (CWW/FOW) ≥ 20

(2) % PM (BIL/LPL) ≥ 20

(3) % PM (BSL/SSP) ≥ 15

d. The protective margins for the MOV arresters selected yield protective margins of:

(1) *Transformer BIL = 650 kV.*

(a) % PM (CWW/FOW) = (715 *kV*/458 *kV* - 1) × 100 = 56%

(b) % PM (BIL/LPL) = (650 *kV*/455 *kV* - 1) × 100 = 43%

(c) % PM (BSL/SSP) = (540 *kV*/339 *kV* - 1) × 100 = 59%

(2) *Transformer BIL = 750 kV.*

(a) % PM (CWW/FOW) = (825 *kV*/458 *kV* - 1) × 100 = 80%

(b) % PM (BIL/LPL) = (750 *kV*/455 *kV* - 1) × 100 = 65%

(c) % PM (BSL/SSP) = (620 *kV*/339 *kV* - 1) × 100 = 83%

(3) *Transformer BIL = 825 kV.*

(a) % PM (CWW/FOW) = (905 *kV*/458 *kV* - 1) × 100 = 98%

(b) % PM (BIL/LPL) = (825 *kV*/455 *kV* - 1) × 100 = 81%

(c) % PM (BSL/SSP) = (685 *kV*/339 *kV* - 1) × 100 = 102%

d. Summary.

(1) As noted from the transformer BIL / surge arrester coordination plots (Figure B-1), the minimum protective margins are much greater than the design standards, due to the better protective characteristics of MOV surge arresters.

(2) A high-voltage winding BIL rating of 750 *kV* BIL for the 230-*kV* nominal system voltage shall be selected for the transformers. These BIL selections will provide the following advantages: (a) reduction in transformer procurement costs, (b) reduction in transformer losses, (c) better coordination with the BIL rating structure of the system, and (d) reduction in the physical size of the transformer. Item (d) is due consideration because of vault size limitations.

B-6. Sample Study B2, Transformer Bushings Rating

a. Objective. The objective of this study is to determine the proper ratings for the bushings and bushing current transformers on the replacement generator step-up (GSU) transformers.

b. References. The following references were used in the performance of this study. Complete citations can be found in Appendix A of this document, "References."

(1) ANSI C76.1-1976 / IEEE Std. 21-1976.

(2) ANSI C76.2-1977 / IEEE Std. 24-1977.

(3) ANSI C57.13-1978.

(4) Main Unit Generator Step-up Transformer Replacement, Transformer *kVA* Rating Study.

(5) Main Unit Generator Step-up Transformer Replacement, BIL / Surge Arrester Coordination Study.

c. Procedure. As summarized in the referenced studies, the transformers shall be rated as follows:

46,000 *kVA*
13.2 *kV* △/230 *kV* Y
750 *kV* High-Voltage Winding BIL
110 *kV* Low-Voltage Winding BIL

d. Bushing ratings and characteristics. As outlined in IEEE Std. 21-1976, performance characteristics based upon definite conditions shall include the following:

- Rated maximum line-to-ground voltage
- Rated frequency
- Rated dielectric strengths
- Rated continuous currents

The bushings will not be subject to any unusual service conditions.

(1) *Rated maximum line-to-ground voltage.*

(a) Based upon ANSI C57.12.00, the relationship of nominal system voltage to maximum system voltage is as follows:

Nominal System Voltage	Maximum System Voltage
230 *kV*	242 *kV*

(b) The maximum line-to-ground voltage is therefore:

Maximum System Voltage	Maximum Line-To-Ground Voltage
242 *kV*	139.7 *kV*

(c) Line voltages are commonly operated between the nominal and maximum system voltages. Based on this, the selection of maximum line-to-ground voltages will be chosen as 5 percent higher than the ANSI suggested values to avoid overheating of the bushings during normal operating conditions. This leads to bushing selections with the following Rated Maximum Line-To-Ground Voltage, Insulation Class, and BIL characteristics:

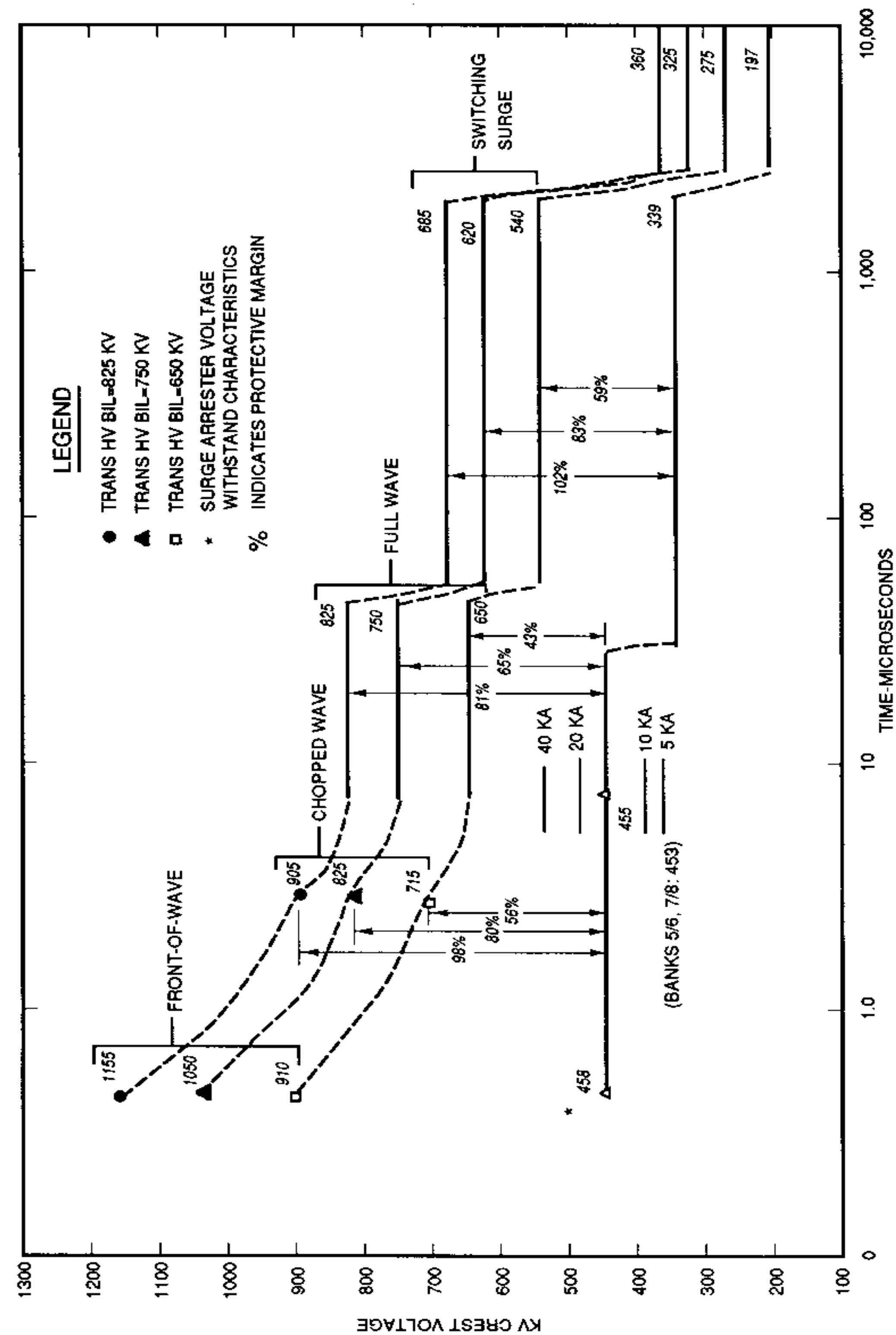

Figure B-1. Transformer BIL/Surge Arrester Coordination Plots

- Line Voltage: 230 *kV*

- Bushing Insulation Class: 196 *kV*

- Bushing BIL: 900 *kV*

- Rated Maximum Line-to-Ground Voltage: 146 *kV*

(d) The low-voltage terminal bushings shall be insulated at the same BIL as the generator windings, i.e., 110 *kV* BIL. This corresponds to an insulation class of 15 *kV*.

(e) The neutral terminal bushings shall be insulated at 150 *kV* BIL, corresponding to an insulation class of 25 *kV*.

(2) *Rated frequency.* The frequency at which the bushings shall be designed to operate is 60 Hz.

(3) *Rated dielectric strengths.* The rated dielectric strengths for the transformer bushings, expressed in terms of specific values of voltage withstand tests, shall be as follows:

(a) 230 *kV* system high-voltage bushings.

- 60 Hz, 1-min Dry Voltage Withstand Test: 425 *kV* rms

- 60 Hz, 10-sec Wet Voltage Withstand Test: 350 *kV* rms

- Full Wave Impulse Voltage Withstand Test: 900 *kV*

- Chopped Wave Impulse - *kV* Crest, 2μsec Withstand: 1160 *kV*

- Chopped Wave Impulse - *kV* Crest, 3μsec Withstand: 1040 *kV*

(b) 13.2 *kV* low-voltage bushings.

- 60 Hz, 1-min Dry Voltage Withstand Test: 50 *kV* rms

- 60 Hz, 10-sec Wet Voltage Withstand Test: 45 *kV* rms

- Full Wave Impulse Voltage Withstand Test: 110 *kV*

- Chopped Wave Impulse - *kV* Crest, 2μsec Withstand: 142 *kV*

- Chopped Wave Impulse - *kV* Crest, 3μsec Withstand: 126 *kV*

(c) Neutral bushings.

- 60 Hz, 1-min Dry Voltage Withstand Test: 60 *kV* rms

- 60 Hz, 10-sec Wet Voltage Withstand Test: 50 *kV* rms

- Full Wave Impulse Voltage Withstand Test: 150 *kV*

- Chopped Wave Impulse - *kV* Crest, 2μsec Withstand: 194 *kV*

- Chopped Wave Impulse - *kV* Crest, 3μsec Withstand: 172 *kV*

(4) *Rated continuous currents.*

(a) The following are the rated currents for the transformer bank, based upon the maximum *k*VA generating capacity of each generating unit:

- Two generators shall be connected to the transformer bank. The maximum *k*VA rating of each generator is 69,000 *k*VA. The total of the generator rated currents for these units is, therefore:

$$I = \frac{2S_{3\phi}}{\sqrt{3}\,V_L} = \frac{(2)\,69{,}000\,kVA}{\sqrt{3}\,(13.8\,kV)} = 5{,}774\ Amps$$

- Total rated low-voltage terminal current for delta connected transformers:

$$I_{\triangle} = \frac{I}{\sqrt{3}} = \frac{5{,}774\ Amps}{\sqrt{3}} = 3{,}334\ Amps$$

- Rated line current:

$$I_L = 5{,}774\ Amps \times \frac{13.2\,kV}{230\,kV} = 331\ Amps$$

(b) Based on the above data, the suggested minimum bushing rated current requirements shall be as follows:

• High-Voltage Bushing Minimum Current Rating: 400 Amperes

• Neutral Bushing Minimum Current Rating: 400 Amperes

• Low-Voltage Bushing Minimum Current Rating: 3,500 Amperes

e. Bushing current transformer (CT) ratings and characteristics. Two standard multi-ratio bushing-type CT's for relaying service shall be installed in each of the 230-*kV* transformer high-voltage bushings for the bank, conforming to accuracy classification 'C', rated 400/5. These CT's shall be used for transformer differential relaying and line protective relaying.

B-7. Sample Study B3, Transformer Efficiency

a. Objective. The objective of this study is to estimate the transformer efficiencies for the proposed replacement generator step-up (GSU) transformers.

b. References. The following references were used in the performance of this study. Complete citations can be found in Appendix A of this document, "References."

(1) Main Unit Generator Step-up Transformer Replacement, Transformer *k*VA Rating Study.

(2) Main Unit Generator Step-up Transformer Replacement, BIL/Surge Arrester Coordination Study.

(3) Westinghouse Electric Corporation. 1964 (located at end of study).

c. Procedure. The calculations for estimating the transformer losses and efficiency calculations shall be based on the Westinghouse Technical Data Bulletin No. 48-500. The following steps will be used in determining this data:

(1) Determine the insulation level of the transformer.

(2) Determine the equivalent two winding 65 °C reference product factors.

(3) Determine the basic product factor from the Table A: 65 °C reference product factors.

(4) Adjust for special features.

(5) Determine the ratio of losses.

(6) Determine the losses.

(7) Determine transformer estimated efficiency.

*d. Transformer bank: 46,000 k*VA, 1ϕ, 13.2 *kV* △/230 *kV* Y, FOA cooled transformers.

(1) *Transformer BIL rating.*

(a) Low-voltage windings: 110 *kV* BIL.

(b) High-voltage windings: 750 *kV* BIL.

(2) *Equivalent two-winding 65 °C self-cooled MVA.* For FOA type cooling rated at 65 °C, the specified *MVA* is for self-cooling.

(3) *Basic product factor determination (P_e).* Basic reference product factor:

$$P_e = A\sqrt{MVA} + \frac{B}{\sqrt{MVA}}$$

(a) As taken from Table A, A = .0001590, B = .2564

(b) Conversion of the *MVA*(1ϕ) to *MVA*(3ϕ) is required to calculate the product factor.

$MVA(3\phi) = 2 \times MVA(1\phi) = 2 \times 46\ MVA = 92\ MVA$

(c) Therefore, the base product factor (P_e) is:

$$P_e = .0001590\sqrt{92} + \frac{.2564}{\sqrt{92}} = .028257$$

(4) *Adjust P_e for % adders (P_r).* The base product factor calculated in (c) should be adjusted further for special features. The adjusted base product factor, P_r, is calculated as follows:

$$P_r = (1 + \frac{\Sigma PercentAdditions}{100}) \times P_e$$

(a) From Table B, on page 12 of the Westinghouse document, the percent additions are:

Front of Wave Impulse Test: 5%

(b) Final adjusted base product factor:

$P_r = .028257 \times (1+.05) = .029669$

(5) *Loss ratio (R).* The ratio of losses (NL *kW*/L *kW*), applying to the reference product factors, for transformers with the high-voltage winding BIL between 550 and 750 *kV*, is calculated as follows:

$R = 2.75 - .182 \ 1n \ MVA$

$R = 2.75 - .182 \ln 46 = 2.053$

(6) *Determination of losses.*

(a) The percent no-load loss is given by:

$$\%Fe = \sqrt{\frac{P}{R}} = \sqrt{\frac{.029669}{2.053}} = .120214$$

(b) No-load loss is given by:

$$No\text{-}Load\ Loss = \frac{MVA}{100} \times \%Fe$$

$$= \frac{46}{100} \times .120214 = .055299\ MW$$

No-Load Loss = 55.30 *kW*

(c) Total loss is given by:

Total Loss = (*R*+1) × No-Load Loss

Total Loss = (2.053 + 1) × 55.30 *kW* = 168.83 *kW*

(d) Load loss is given by:

Load Loss = Total Loss - No-Load Loss
= 168.83 *kW* - 55.30 *kW*

Load Loss = 113.53 *kW*

(7) *Estimated efficiency* (η). The transformer estimated efficiency is given by:

$$\eta = \frac{MVA}{MVA + Total\ Losses} \times 100\%$$

$$= \frac{46}{46 + .168830} \times 100\% = 99.63\%$$

B-8. Sample Study B4, Transformer Loss Evaluation

a. Objective. The objective of this study is to establish the loss evaluation and penalty factors, and determine an auxiliary cooling loss evaluation factor, for use in the construction specifications for the new main unit generator step-up replacement transformers.

b. References. The following reference was used in the performance of this study. A complete citation can be found in Appendix A of this document, “References.”

(1) “Main Unit Generator Step-Up Transformer Replacement, Transformer Efficiency Study.”

(2) Guide Specification CE-2203. Power Transformers.

c. Discussion.

(1) *Pertinent values for computations.* The following sample values will be used in the computations for loss evaluation:

(a) Value of replacement energy: 15.94 mills/KW-hr

(b) Value of replacement capacity: $267,800/MW-yr = $30.57/KW-yr

(c) Alternative cost of Federal financing interest rate: 8.5%

(d) Plant capacity factor: 54%

(2) *Determination of rates of evaluation.* The evaluation of transformer efficiency for use in determining award of the contract should be based on the same value per *kW* of loss used in determining the evaluation of efficiency of the associated main generators. This value of one kilowatt of loss is the capitalized value of the annual capacity and energy losses based on the average annual number of hours of operation. The transformer load used for efficiency evaluation should correspond approximately to the generator load used for evaluation of generator efficiency. For class FOA transformers, 87 percent of rated load at 1.0 power factor shall be used.

Westinghouse Electric Corporation
Medium Power Transformer Division
Sharon, Pa. 16146

Large Power Transformer Division
Muncie, Indiana 47302

September 15, 1981
Supersedes TD 48-660, pages 1-24,
dated November 23, 1964

Mailed to: E, D, C/2091, 2094/DB

Power Transformers

Table of Contents

General Information
The information and instructions contained in this technical data cover power transformers rated as follows: Oil-Immersed, Self-Cooled, Forced-Air Cooled, and Forced-Oil Cooled.

The kVA ratings below are self-cooled. 2500 through 10000 kVA, 3-Phase, greater than 350 kV BIL or with Load Tap Changing (LTC), 10001 kVA and larger, 3-Phase, all Basic Impulse Levels (BIL) with or without LTC, 1667 through 3333 kVA, 1-Phase, 450 through 750 kV BIL or with LTC, 3334 and larger, 1-Phase, all Basic Impulse Levels (BIL) with or without LTC.

Proper Selection
The basic economic considerations in making the proper selection of a power transformer are first cost and operating costs (transformer losses).

In order for the transformer designer to select the proper losses, he must first know the dollars per kilowatt loss that the user of the transformer evaluates both the iron (No-Load) losses and the conductor (Load) losses and at what kVA load these values will be used to evaluate the losses.

The losses determined from the loss product factor and loss ratio rules in this technical data are for reference only and indicate the approximate losses of a transformer on which there is no loss evaluation or when losses are evaluated at values which result in an efficiency multiplier of 1.00 from Rule 2 in Price List 48-500.

Section V

Loss Product Factor and Loss Ratio

The reference product factors are based on the premise that the standard transformer is a 65°C rise transformer and the load losses are to be tested at a standard reference temperature of 85°C in accordance with ANSI C57.12.00. The transformer can however deliver the specified output Kva at other average temperature rises by the addition of the required cooling apparatus. For instance, by the addition of the necessary cooling apparatus the transformer can deliver the specified output at an average winding temperature rise of 55°C. Once this transformer has been adjusted to be a 55°C rise transformer it will have a supplemental 65°C rise rating equal to 1.12 times the 55°C rating.

The equivalent 65°C two-winding parts to be used in calculating the loss product factor is the 65°C self-cooled Kva two-winding parts of a transformer specified to deliver the required output Kva at an average winding temperature rise of 65°C or the self-cooled Kva parts calculated by using the output Kva specified at 55°C rise for a 55°C/65°C transformer. The losses for the 55°C rise transformer are adjusted to be tested at a 75°C reference temperature rather than 85°C by dividing the calculated load losses by 1.04. The load losses at the 65°C rise supplemental rating of a 55°/65°C transformer are 1.2544 (1.12 squared) times the load losses at the 55°C rise rating times 1.04 to correct the losses to the reference temperature of 85°C.

In calculating the loss product factor and loss ratio for a power transformer the following procedure must be followed:

First: Determine the insulation level from section III.

Second: Determine the equivalent two winding 65°C self-cooled mva.*

Third: Determine the basic product factor from the table A: 65°C reference product factors.

Fourth: Adjust for special features.

Fifth: Determine the ratio of losses.

Sixth: Determine the losses.

*The equivalent two-winding parts are the sum of the mva's of all the windins divided by two.

To calculate the equivalent 2 winding Kva parts to be used in developing the basic product factor for an autotransformer use the following formulas to calculate the Kva's of the windings.

Series winding Kva =

$$(\text{HV}^* \text{ max.} - \text{LV}^* \text{ min}) \left(\frac{\text{OA Kva}}{\text{HV}^{**} \text{ Min}} \right),$$

Common winding Kva =

$$\text{LV}^* \text{ max} \left(\frac{\text{OA Kva}}{\text{LV}^{**} \text{ Min}} - \frac{\text{OA Kva}}{\text{HV}^{**} \text{ Max}} \right)$$

Tertiary winding Kva = .35 × largest of series or common

*Do not use LTC tap voltages, use the de-energized tap voltages in Kv.

**Use LTC tap voltages and/or de-energized tap voltages, in Kv, that determine this voltage at which full nameplate Kva occurs as either input or output.

Step 1: Base Product Factor

The base product factor, based on the equivalent 65°C self-cooled two-winding mva parts, is calculated from Table A by selecting the proper A and B factor for the proper BIL and the following formula.

$$\text{Product Factor} = A\sqrt{\text{MVA}} + \frac{B}{\sqrt{\text{MVA}}}$$

The calculated product factor should be rounded to the nearest five decimal places.

Table A:
65°C Reference Product Factors
(3-phase transformers)

Product factors are to be based on the equivalent 65°C two-winding parts.

BIL-Kv	A	B
110	.0001760	.2300
150	.0001758	.2317
200	.0001750	.2337
250	.0001745	.2358
350	.0001740	.2399
450	.0001730	.2440
550	.0001700	.2481
650	.0001660	.2522
750	.0001590	.2564
825	.0001500	.2594
900	.0001380	.2625
1050	.0001240	.2695
1175	.0001070	.2800
1300	.0000870	.2940
1425	.0000640	.3260
1550	.0000420	.3510
1675	.0000095	.3880
1800	−.0000392*	.4299
1925	−.0000744*	.4750
2050	−.0001134*	.5219

*These are negative numbers.

55°C Losses

No-load losses are the same as 65°C no-load losses

Load losses = 65°C load losses/1.04

Single-phase transformer product factors

Multiply the 1φ MVA times 2, then use the result to calculate the product factor from the 3φ table.

Step 2: Percentage Additions to Base Product Factor

The base product factor calculated in accordance with Step 1, should be adjusted further for special features in accordance with Table B. The summation of all the percent additions for special features is to be multiplied times the base product factor as follows:

$$\left(1 + \frac{\Sigma \text{ Percent Additions}}{100}\right) \times \begin{array}{c}\text{Base Product}\\ \text{Factor}\end{array}$$

This determines the final adjusted base product factor.

Table B
Percentage Additions to Base Product Factor

	% Adders
More than two windings	
3-windings	15
≥4-windings	20
Ground Neutral Service**	
≤350 (BIL)*	0
450	− 1.0
550	− 1.5
650	− 2.0
750	− 2.5
825	− 2.5
900	− 3.0
Windings other than H.V. BIL other than Auto:	
110	0
150	2.0
200	4.0
250	8.0
350	16.0
450	22.0
550	29.0
650	36.0
750	42.0
825	47.0
900	52.0
BIL of Common Winding of Autotransformer:	
110	0
150	2.0
200	4.0
250	6.0
350	11.0
450	14.0
550	17.0
650	20.0
750	23.0
825	25.0
900	27.0
Special Front of Wave Impulse Test	5.0
Split HV or LV Winding	2.0
LTC	10.0 or % reg.* if greater
Series Multiple:	
2 Multiples	5
3 Multiples	10
4 Multiples	12
Station Auxiliary If Rule 5K in Price List 48-500 applies.	−15

*e g ±15% LTC would add 15.0.
**Does not apply to autotransformers.

Step 3: Multiplier on Adjusted Base Product Factor for Other Than Two-Winding Transformer

The base adjusted product factor, calculated in accordance with Steps 1 and 2, should be adjusted for other than two-winding transformers and autotransformers if applicable, to adjust for the loading Kva and equivalent self-cooled two-winding Kva parts. The product factor, Pr, determined in accordance with this step will be the product factor of the losses at the **OA nameplate rating.**

Pr = Pe × K

Where:

Pr = Product factor corresponding to the OA nameplate rating, or equivalent if the transformer is FOA only*

Pe = Base reference product factor for the equivalent self-cooled two-winding Kva parts, calculated in accordance with Steps 1 and 2.

$$K = A \times \left(\frac{\text{equivalent self-cooled two-winding kva parts}}{\text{OA Nameplate rating}} \right)^2$$

Where; for autotransformer, A = .65
for other than autotransformer, A = .85

* To obtain the load losses at the FOA rating, multiply the load losses calculated with this product factor by 2.78.

Loss Ratio: The ratio of losses (NL KW/L kw) applying to the reference product factors can be calculated from table C for the standard 65°C rise unit. The 55°C rise loss ratio is the 65°C rise ratio + 1.04.

Table C. Loss Ratios
BIL KV of the highest voltage winding

≤350	>350 ≤550	>550 ≤750	>750 ≤900	>900 ≤1175	>1175 ≤1425	>1425
5.45-.516 Ln MVA	3.82-.270 Ln MVA	2.75-.182 Ln MVA	2.50-.111 Ln MVA	2.26-.078 Ln MVA	2.13-.060 Ln MVA	2.08-.058 Ln MVA

where:
Ln MVA is the natural logarithm of the MVA

The loss ratio calculated from Table C must be further adjusted in accordance with Table D. Any multiplier adjustments will be made to the multiplier adjusted ratio by multiplying by:

$$\left(1 + \frac{\Sigma \text{ Percent adders}}{100}\right)$$

Table D: Adjustment to Loss Ratio

Special Feature	Multiplier	% Adder
Frequency 50 Hertz	1.2	
Special Impedance	$\sqrt{\frac{\text{IZ spec.}}{\text{IZ Std.}}}$	
Over Excitation percent above standard for either no-load or full-load voltage		
5%		25
10%		35
15%		45
20%		60
25%		70
Reduction in Sound level Based on loss evaluation in $/kw applied to no-load loss		
≤1000		2 per db
>1000 ≤2000		1 per db
>2000		0
Station Auxiliary If Rule 5K in Price List 48-500 applies, add		35①
Autotransformers	$\sqrt{r}$②	
LTC Voltage Regulation Through the Magnetic Circuit. Percent Regulation		
5		25
10		35
15		45

① Do not make any further addition for over excitation.

② $r = \frac{HV_{mid} - LV_{rated}}{HV_{mid}}$

Determination of Losses

The percent no load loss (%Fe) and the percent load loss (%Cu) may be determined from the final product factor (P) and the loss ratio (R) by using the following formula:

$$\% \text{ Fe} = \sqrt{\frac{P}{R}} \qquad \% \text{ Cu} = R \times \% \text{ Fe}$$

$$\text{No load loss (kw)} = \frac{\text{kva}}{100} \times \% \text{ Fe}$$

$$\text{Total loss (kw)} = (R + 1.0) \times \text{no load loss}$$

Power Required for Fans and Pumps

When it is required that the losses due to the fans and pumps be guaranteed they must be given separately from the transformer losses.

The loss for the fans and pumps is based on the total transformer loss at the fan-cooled or forced-cooled rating and shall be not less than the following:

for standard forced-air cooling (OA/FA) .... 2% (max.)
for OA/FA/FA .... 2% (max.)
for OA/FOA/FOA .... 5% (max.)
for forced-oil cooled with air cooler (FOA) .... 5% (max.)
for forced-oil-cooled with water cooler (FOW) .... 3½% (max.)

Exciting Current (Estimated)

For estimated values of exciting current and no load losses for 60 cycle transformers use values calculated from the following table:

Percent Rated Voltage	Percent Exciting Current				Percent No-Load Loss			
	No-Load Loss Evaluation-$/kw				No-Load Loss Evaluation-$/kw			
	≤500	>500 ≤2500	>2500 ≤5000	>5000	≤500	>500 ≤2500	>2500 ≤5000	>5000
80	2A	1.5A	1A	0.8A	0.54A	0.59A	0.62A	0.65A
90	4A	3A	2A	1.2A	0.72A	0.77A	0.80A	0.82A
100	12A	6A	4A	2A	1.00A	1.00A	1.00A	1.00A
105	23A	10A	6A	3A	1.25A	1.21A	1.15A	1.12A
110	43A	16A	9A	4A	1.80A	1.40A	1.33A	1.25A
117.5	....	50A	22A	6A	....	2.10A	1.70A	1.45A

where A is percent no load loss (% Fe) determined above. For frequency other than 60 cycles, multiply the 60 cycle percent exciting current obtained above by:

50 cycles **1.1**

Determination of Loss Level

The evaluation $/kw for no-load and load losses will affect the optimized design losses of a transformer. Typically, the dollar evaluations shown in Table E, will result in approximate percent product factors and loss ratios as shown. When estimating the efficiency multiplier for a design that falls outside the usual grid position for the specified evaluation dollars use the efficiency multiplier in table 2a (PL 48-500) corresponding to the design's actual percent product factor grid position in Table E.

Table E

No Load $/kw \ (OA) Load② $/kw								
	55°C	≤650	>650 ≤1300	>1300 ≤1950	>1950 ≤2600	>2600 ≤3900	>3900 ≤5200	>5200 ≤
	65°C	≤500	>500 ≤1000	>1000 ≤1500	>1500 ≤2000	>2000 ≤3000	>3000 ≤4000	>4000 ≤
≤500	% PF	100	74	68	63	59	55	52
	R①	3.5	3.4	3.3	3.0	2.8	2.6	2.4
>500 ≤1000	% PF	75	70	64	61	57	54	51
	R①	3.6	3.5	3.4	3.1	2.9	2.7	2.5
>1000 ≤1500	% PF	71	67	61	59	55	52	50
	R①	3.7	3.6	3.5	3.3	3.1	2.8	2.5
>1500 ≤2000	% PF	68	63	60	57	54	52	50
	R①	3.7	3.6	3.5	3.3	3.1	2.8	2.5
>2000 ≤2500	% PF	66	62	59	56	54	51	49
	R①	3.8	3.7	3.6	3.4	3.2	2.9	2.6
>2500 ≤3000	% PF	64	61	58	55	53	51	49
	R①	3.8	3.7	3.6	3.4	3.2	2.9	2.6
>3000 ≤4000	% PF	62	60	57	55	52	51	49
	R①	3.9	3.8	3.7	3.5	3.3	3.0	2.7
>4000 ≤5000	% PF	60	58	55	53	52	50	48
	R①	4.0	3.9	3.8	3.6	3.4	3.1	2.8
>5000	% PF	58	56	54	52	51	50	48
	R①	4.1	4.0	3.9	3.7	3.5	3.2	2.9

① For autotransformers, the loss ratio must be multiplied by $\sqrt{\frac{\text{HV mid} - \text{LV rated}}{\text{HV mid}}}$

② For FOA units, convert load $/kw to an equivalent OA basis by multiplying ($/kw) × 2.78.

(a) The rate of evaluation for efficiency is calculated as present worth, as follows:

- R = rate of evaluation
- EV = energy value
- CV = capacity value
- CF = capacity factor
- PWF = present worth factor

So,

$$R = (PWF)\,((365)\,(24)\,(EV)\,(CF) + CV)$$

The present worth factor (PWF) for 35 years at 8.5% is:

$$PWF = (\frac{P}{A}, 8.5\%, 35) = \frac{(1+.085)^{35}-1}{.085(1+.085)^{35}} = 11.088\,YR$$

$$R = (11.088 YR) \times ((365 \frac{DAYS}{YEAR}) \times (24 \frac{HOURS}{DAY}) \times (.01594 \frac{\$}{KW-HR}) \times (.54) + 30.57 \frac{\$}{KW-YR})$$
$$= 1{,}175 \frac{\$}{KW}$$

(b) Transformer efficiency and losses. Transformer input shall be based upon 87 percent of rated load at 1.0 power factor of the connected generators. The transformer bank has two generators connected, each rated at 69,000 kVA at 1.0 power factor. The total input to each single-phase transformer under these conditions is therefore:

$$Input = \frac{(2) \times (69{,}000\ kVA) \times (1.0\ pf) \times (0.87)}{3\ transformers}$$
$$= 40{,}020\ kW$$

Transformer output shall be based upon the specified efficiency of 99.63 percent:

$$Output = 40{,}020\ kW \times (99.63\%) = 39{,}872\ kW$$

Transformer loss is therefore

$$Loss = 40{,}020\ kW - 39{,}872\ kW = 148\ kW$$

(c) Rate of evaluation for each 1/100% of transformer efficiency. Transformer losses per 1/100% of transformer efficiency is:

$$Loss\ per\ 1/100\% = \frac{148\ kW}{(100 - 99.63) \times (100)} = 4.00\ kW$$

The rate of evaluation per 1/100 percent of efficiency is:

$$Rate\ of\ evaluation = (1{,}175.02\ \frac{\$}{kW}) \times (4.00\ \frac{kW}{1/100\%\ eff})$$
$$= 4{,}700\ \frac{\$}{1/100\%\ eff}$$

(3) *Application of rates of evaluation to contract bid and penalty for failure to meet guaranteed efficiency.* The calculated rate of evaluation per 1/100 percent of transformer efficiency shall be used during the bid evaluation to credit the bid price for each 1/100 percent of efficiency that the guaranteed value exceeds the specified minimum value of 99.63 percent. After final testing of the transformer, twice the rate of evaluation shall be applied as a penalty for each 1/100 percent of efficiency less than the guaranteed value.

(4) *Auxiliary cooling loss.*

(a) Guide Specification CE-2203 states the following:

> In the evaluation of Transformer Auxiliary Power, the power required for motor-driven fans and oil-circulating pumps should be evaluated on the basis that each horsepower of motor rating in excess of the number of horsepower excluded from evaluation is equal in value to approximately 40 percent of the capitalized value of one kW of loss used in the transformer efficiency evaluation.

(b) The rate of evaluation for transformer auxiliary power for FOA cooled transformers is given by:

$$Rate\ of\ evaluation = \$1{,}175 \times 40\% = \frac{\$470}{hp}$$

(c) The total horsepower of motor-driven fans and oil pumps excluded from evaluation for each size of transformer is given by:

Total losses based on 99.6% estimated efficiency:

$$\frac{46{,}000\ kVA}{99.6\%} - 46{,}000\ kVA = 184.74\ kW$$

Total auxiliary loss in *hp* excluded from evaluation:

$$184.74\ kW \times \frac{.05\ hp}{kW} = 9.24\ hp$$